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A Nusser

Technion – Israel Institute of Technology

L. N. da Costa

European Southern Observatory

E Branchini

University of Groningen

M. Bernardi

The University of Chicago

M V. Alonso

Argentine National Observatory

See next page for additional authors

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Authors

A Nusser, L. N. da Costa, E Branchini, M. Bernardi, M V. Alonso, and G Wegner

Comparison of the ENEAR Peculiar Velocities with the *PSCz* Gravity Field

Adi Nusser¹, Luiz N. da Costa^{2,3}, Enzo Branchini⁴, Mariangela Bernardi⁵,
M. V. Alonso⁶, Gary Wegner⁷, C. N. A. Willmer^{3,8}, P. S. Pellegrini³

¹*Physics Department, Technion- Israel Institute of Technology, Haifa 32000, Israel*

²*European Southern Observatory, Karl-Schwarzschild Str. 2, D-85748 Garching b. München, Germany*

³*Observatório Nacional, Rua General José Cristino 77, Rio de Janeiro, R. J., 20921, Brazil*

⁴*Kapteyn Institute, University of Groningen, Landleven 12, 9700 AV, Groningen, The Netherlands*

⁵*The University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA*

⁶*Observatorio Astronómico de Córdoba, Laprida 854, Córdoba, 5000, Argentina*

⁷*Dept. of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, U.S.A*

⁸*UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, U.S.A*

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ABSTRACT

We present a comparison between the peculiar velocity field measured from the ENEAR all-sky $D_n - \sigma$ catalog and that derived from the galaxy distribution of the *IRAS PSCz* redshift survey. The analysis is based on a modal expansion of these data in redshift space by means of spherical harmonics and Bessel functions. The effective smoothing scale of the expansion is almost linear with redshift reaching 1500 km s^{-1} at 3000 km s^{-1} . The general flow patterns in the filtered ENEAR and *PSCz* velocity fields agree well within 6000 km s^{-1} , assuming a linear biasing relation between the mass and the *PSCz* galaxies. The comparison allows us to determine the parameter $\beta = \Omega^{0.6}/b$, where Ω is the cosmological density parameter and b is the linear biasing factor. A likelihood analysis of the ENEAR and *PSCz* modes yields $\beta = 0.5 \pm 0.1$, in good agreement with values obtained from Tully-Fisher surveys.

Key words: cosmology: observations – dark matter – large scale structure of Universe

1 INTRODUCTION

In the standard picture for the formation of cosmic structures via gravitational instability the peculiar velocity of a galaxy is generated by fluctuations in the mass distribution. For galaxies outside virialized systems, linear perturbation theory predicts

$$\mathbf{v}(\mathbf{r}) \approx \frac{\Omega^{0.6} H_o}{4\pi} \int d^3 r' \delta_m \frac{(\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}, \quad (1)$$

where Ω is the mass density parameter, H_o is the Hubble constant and δ_m is the mass density fluctuation field. If the relationship between the galaxy distribution, δ_g , and δ_m is approximately linear, $\delta_g = b \delta_m$, then the parameter $\beta = \Omega^{0.6}/b$ can be derived from the comparison between the observed peculiar velocity field and that predicted from the galaxy distribution. A particularly useful method for performing a velocity-velocity comparison is the modal expansion method developed by Nusser & Davis (1995, hereafter ND95). This method expands the velocity fields by means of smooth functions defined in redshift space, thus alleviating the Malmquist biases inherent in real space analysis. Fur-

thermore, the modal expansion filters the observed and predicted velocities in the same way, so that the smoothed fields can be compared directly. Because the number of modes is substantially smaller than the number of data points, the method also provides the means of estimating β from a likelihood analysis carried out on a mode-by-mode basis, instead of galaxy-by-galaxy. The similar smoothing and the mode-by-mode comparison substantially simplify the error analysis. The modal expansion method has previously been used in comparisons between the 1.2 Jy *IRAS* predicted velocities and observed velocities inferred from Tully-Fisher (TF) measurements (Davis, Nusser & Willick 1996, hereafter DNW, da Costa et. al. 1998). In this paper, we perform a similar analysis using the recently completed redshift-distance survey of early-type galaxies (hereafter ENEAR, da Costa et al. 2000) and the *IRAS PSCz* redshift survey (Saunders et. al. 2000). Because of differences in the nature of the data sets considered some slight changes in the method are required and are described below. Our goal is to investigate how well the velocity field mapped by early-type galaxies matches the velocity field inferred from the *PSCz* survey, and to obtain the parameter β yielding the best match.

In section 2, we briefly describe the ENEAR redshift-distance catalog. In section 3, we describe the modal expansion method as used here, present maps of the ENEAR and *PSCz* radial peculiar velocity field and perform a likelihood analysis to derive β . A brief summary of our conclusions is presented in section 5.

2 DATA

We use a sub-sample extracted from the all-sky ENEAR redshift-distance survey (da Costa et al. 2000) comprising 578 objects within $cz \leq 6000 \text{ km s}^{-1}$, 355 field galaxies and 223 groups/clusters. Galaxies have been objectively assigned to groups and clusters using redshifts taken from complete redshift surveys sampling the same volume. Individual galaxy distances were estimated from an inverse $D_n - \sigma$ template relation derived by combining cluster data (e.g., Bernardi et al. 2000). The cluster sample consists of 569 galaxies in 28 clusters. Over 80% of the galaxies in the magnitude-limited sample and roughly 60% of the cluster galaxies have new spectroscopic and photometric data obtained by the ENEAR survey. Multiple observations using different telescope/instrument configurations ensure the homogeneity of the data. Furthermore, the sample completeness is uniform across the sky.

3 THE MODAL EXPANSION

An unbiased estimate of $\beta = \Omega^{0.6}/b$ can be obtained from the comparison between smooth velocity fields with similar spatial resolution, derived from the ENEAR and *PSCz* data. To generate smooth fields we expand the peculiar velocities of both data in terms of smooth base functions. The expansion carried out here shares the general properties of that used by ND95, but differs in details. In their application to TF catalogs, ND95 defined $P_i \equiv 5 - \log(1 - u_i/s_i)$, where $s_i = cz_i$ is the galaxy redshift in km s^{-1} and u_i its radial peculiar velocity. The function P was then expressed by an expansion involving smooth functions. The final estimate of the smoothed velocity field was that obtained by minimizing the scatter of the rotational speeds given the magnitudes in the inverse TF relation. The scatter was also simultaneously minimized with respect to the parameter of the TF relation. This led to an unbiased calibration of the inverse TF relation because the sample was mainly magnitude selected. The galaxy angular size and velocity dispersion in the $D_n - \sigma$ relation do not uniquely fix the magnitude according to which the ENEAR sample is selected. So simultaneous minimization might lead to a biased estimate of the parameters of the $D_n - \sigma$ relation. Although the bias is mild we use the calibration of the *inverse* $D_n - \sigma$ given by Bernardi et al. (2000) by a regression of σ on D_n in clusters. We also express the peculiar velocity, u , rather than the function P in terms of smooth functions. Another difference is that ND95 used TF catalogs with all galaxies having the same relative distance error which allowed an additional simplification in the application of the modal expansion method, namely, the expansion in terms of orthogonal smooth functions. This made the TF velocity error covariance matrices diagonal. In the ENEAR sample, the relative distance error is not the same

for all objects (galaxies and groups/clusters), so using orthogonal functions does not offer any further simplification since the ENEAR error matrix remains non-diagonal. The lack of orthogonality slightly complicates the error analysis but does not affect the efficiency of the expansion. Choosing the spherical harmonics and Bessel functions to be our base smooth functions we write the radial peculiar velocity model as

$$\tilde{u}(s, \theta, \phi) = \sum_{l,m,n} \alpha_{nlm} [j'_l(k_n y(s)) - c_{l1}] Y_{lm}(\theta, \phi) \quad (2)$$

where the sum is over $m = -l$ to $+l$, $l = 0$ to l_{max} , and $n = 0$ to n_{max} . For the reasons given in DNW, we formulate our model to describe the velocity field with respect to the motion of the Local Group. The constant c_{l1} is non-zero only for the dipole term ensuring that $u = 0$ at the origin. The function $y(s)$ in the argument of the Bessel functions makes their oscillations match the radial distribution of the ENEAR data. Here we take $y^2 = \ln[1 + (\frac{s}{1000})^2]$, but other similar forms can be used as well. Also the expansion does not include a Hubble-like flow ($u \propto s$) so we assume that any such flow has been consistently removed from the ENEAR and *PSCz* velocities. The coefficients α_{nlm} are found by minimizing

$$\chi^2 = \sum \sigma_i^{-2} [\tilde{u}_i - u_i^o]^2 \quad (3)$$

where u_i^o are the raw observed velocities and σ_i is the error of the velocity estimate resulting from observational uncertainties and intrinsic scatter in the $D_n - \sigma$. For field galaxies $\sigma_i = 0.23s_i$ and for groups of galaxies it is reduced by $1/\sqrt{N_g}$, where N_g is the number of galaxies in the group.

4 SMOOTH VELOCITY MAPS AND THE DETERMINATION OF β

We apply the modal expansion method to smooth the raw measured velocities of the 578 ENEAR objects within a redshift of 6000 km s^{-1} (Bernardi et al. 2000). We use 51 modes corresponding to $l_{max} = 4$, $n_{max} = 3$ in (2). The smoothing scale of these functions is linear with redshift and matches the low resolution filter used in da Costa et al. (1998) (see their Figure 1). The smoothed velocities were then derived by minimizing (3) with respect to α_{lmn} assuming an error of $\sigma_i = 0.23s_i/\sqrt{N_g}$ in the raw velocities of the ENEAR objects. The reduced χ^2 per d.o.f. of the fit was 1.017, a satisfactory value in this type of analysis (see DNW, da Costa et al. 1998).

Given an assumed value for β we interpolate the *PSCz* predicted velocity field, computed by Branchini et al. (2000), to the positions of the ENEAR galaxies. Branchini et al. obtained the *PSCz* velocities from the *PSCz* galaxy distribution with a Top-Hat window of width equal to half the mean particle separation at a given redshift. The *PSCz* fields are then expanded in the same orthogonal set of basis functions as employed for the ENEAR velocities. The *PSCz* and ENEAR velocities are guaranteed to have the same resolution because the original smoothing of the *PSCz* density field is small compared to the resolution of the modal expansion.

The smoothed ENEAR velocities are shown in Figure 1,

in redshift shells 2000 km s^{-1} thick. Comparison of this figure and Figure 3 of da Costa et al. (1998) shows that the general flow pattern is remarkably similar. In the case of ENEAR, in the innermost shell very few prominent structures are probed by bright ellipticals. However, in the next two shells a strong dipole pattern can be easily recognized, being of comparable amplitude to that of observed with the SFI galaxies. This dipole corresponds to the reflex motion of the Local Group, with infalling galaxies in the Hydra-Centaurus direction and an outflow towards the Perseus-Pisces complex. The quality of the match can be evaluated from Figure 2 which shows the residual velocity field obtained subtracting the smoothed PSCz field from that of the ENEAR, assuming $\beta = 0.5$. As can be seen the overall agreement is good with only a few more distant galaxies giving large residuals. Note, however, that even though with a larger amplitude, the mismatch seen in the outermost redshift shell at $l \sim 0^\circ, -60^\circ \lesssim b \lesssim -15^\circ$ between ENEAR and PSCz correspond to mismatches in the comparison between SFI and 1.2 Jy IRAS velocity fields. This may correspond to a real mismatch between measured and predicted velocities which deserves further investigation.

The filtered ENEAR and PSCz velocity fields are fully described by the modal expansion coefficients, α_{en} and α_{ps} , of the ENEAR and PSCz fields, respectively. Since the number of these coefficients is significantly smaller than the number of galaxies, it is more efficient to estimate β by comparing the modes rather than the individual galaxy velocities. As in da Costa et al. (1998) we define our best estimate for β as the value that corresponds to the minimum of the pseudo- χ^2

$$\tilde{\chi}^2(\beta) = \sum_{j,j'} [\alpha_{en}^j - \alpha_{ps}^j(\beta)] [\mathbf{T} + \mathbf{M}(\beta)]^{-1} [\alpha_{en}^{j'} - \alpha_{ps}^{j'}(\beta)], \quad (4)$$

where $\mathbf{T} \equiv \langle \delta\alpha_{en}^j \delta\alpha_{en}^{j'} \rangle$ and $\mathbf{M} \equiv \langle \delta\alpha_{ps}^j \delta\alpha_{ps}^{j'} \rangle$ are the error covariance matrices of the coefficients α_{en}^j and α_{ps}^j , respectively. For brevity of notation we have replaced the triplet n, l, m with one index j . The PSCz covariance matrix \mathbf{M} incorporates errors due to (i) the uncertainty in the LG motion, which creates a dipole discrepancy between the ENEAR and the PSCz velocities, (ii) the discreteness in distribution of galaxies which propagates into the velocity field, and (iii) small scale coherent (as in triple valued zones) nonlinear velocities that are not included in the PSCz recovered velocities. Details of how these error contributions are computed are in da Costa et al. (1998). Since the expansion functions are not orthogonal the ENEAR covariance matrix \mathbf{T} has nonzero off-diagonal elements. This matrix is simply the inverse of $\frac{\partial^2 \chi^2}{\partial \alpha_{en}^j \partial \alpha_{en}^{j'}}$ where the derivatives are computed at the minimum of χ^2 given by (3).

Given the covariance matrices, we compute the curve of the reduced $\tilde{\chi}^2(\beta)$ as a function of β , which is shown in the top panel of Figure 3. The curve was computed with an error of 150 km s^{-1} in the estimation of the LG motion and 160 km s^{-1} for the amplitude of nonlinear error in the PSCz field (see da Costa et al. 1998). This amplitude of the nonlinear error was chosen to make the $\tilde{\chi}^2$ per d.o.f equal to unity at the minimum. In their analysis of the SFI and 1.2 Jy IRAS, da Costa et al. (1998) obtained a lower value of 90 km s^{-1} for the amplitude of this error. The difference can be attributed, as expected, to a better match between the

SFI and IRAS velocities and the increased nonlinearities in the PSCz velocity at the positions of the ENEAR galaxies which preferentially reside in high density regions.

The minimum value of the $\tilde{\chi}^2$ is attained at $\beta = 0.5$, with the 1-sigma error being less than 0.1. We note that this result is not sensitive to the exact values adopted for the error estimates. Another statistic indicating the goodness of the match between the fields for various β is the correlation function of the residual $u_{en} - u_{ps}$ between the smoothed ENEAR and PSCz radial velocities. This is shown in the bottom panel of Figure 3 for $\beta = 0.2, 0.5$, and 0.9 . The amplitude of the PSCz field is small for $\beta = 0.2$, so the correlation function for this β is close to the correlation function of u_{en} alone, while the opposite is true for $\beta = 0.9$. On the other hand, for $\beta = 0.5$ the correlation of the residual velocity field is significantly smaller, indicating a good match between the measured and predicted velocity fields.

5 SUMMARY AND DISCUSSION

Using the modal expansion method of ND95 and the recently completed ENEAR redshift-distance survey and the PSCz redshift survey we have carried out a comparison between the observed peculiar velocity field and that predicted from the distribution of PSCz galaxies. We find that the corresponding smoothed fields agree well and the best match is obtained with $\beta = 0.5 \pm 0.1$. This value is intermediate to those derived using the Mark III and SFI catalogs both based primarily on spiral galaxies. It is also consistent with the results obtained by Borgani et al. (2000) using an independent method based on modeling the velocity correlation function. Note, however, that the discrepancy between the values determined from these methods and those obtained from the power spectrum analysis (e.g., Zaroubi et al. 2000) and density-density comparisons (e.g., Sigad et al. 1998) still persist. The good agreement between SFI and 1.2 Jy IRAS and between ENEAR and PSCz implies that the SFI and ENEAR velocity fields are also in good agreement. This suggests that the velocity maps obtained from the new distance-redshift surveys are a fair representation of the underlying velocity field, as the general characteristics of the observed flow fields are independent of the type of galaxies and distance indicators used. The good agreement among the values of β obtained using Mark III, SFI, ENEAR, 1.2 Jy and PSCz catalogs gives further support to low values of β and point toward low-density cosmologies.

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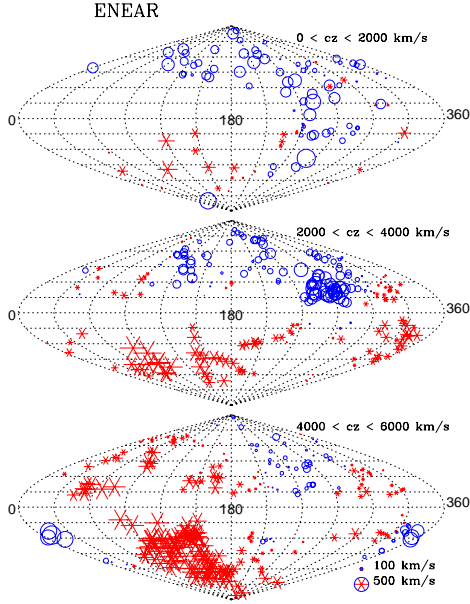


Figure 1. The sky projection in galactic coordinates as seen in the LG frame of the filtered ENEAR velocity field.

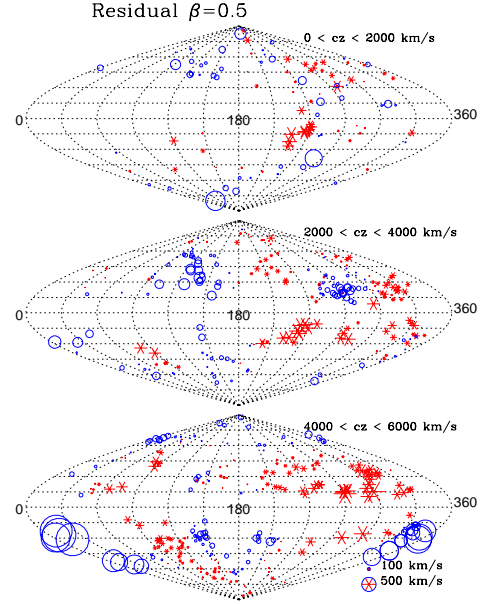


Figure 2. The residual velocity field (ENEAR minus PSCz) for $\beta = 0.5$

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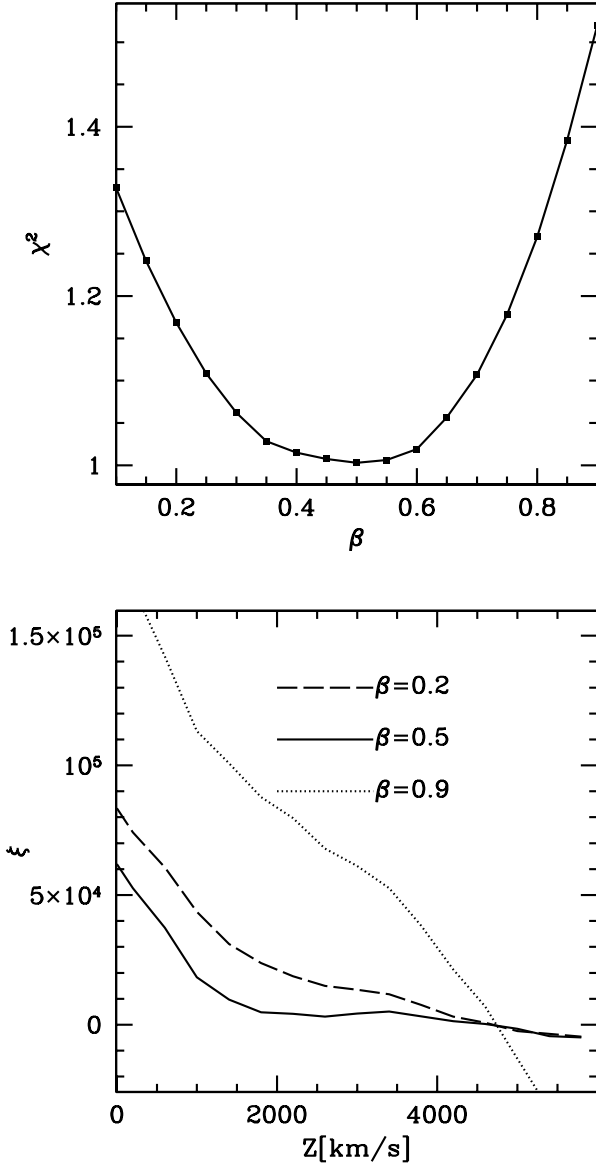


Figure 3. *Top panel:* curve of reduced pseudo- χ^2 versus β computed using equation (5). *Bottom panel:* the correlation function of the velocity residual field for $\beta = 0.2, 0.5$ and 0.9 .